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A review of solar photovoltaic technologies

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ABSTRACT

Global environmental concerns and the escalating demand for energy, coupled with steady progress in renewable energy technologies, are opening up new opportunities for utilization of renewable energy resources. Solar energy is the most abundant, inexhaustible and clean of all the renewable energy resources till date. The power from sun intercepted by the earth is about 1.8×10^{11} MW, which is many times larger than the present rate of all the energy consumption. Photovoltaic technology is one of the finest ways to harness the solar power. This paper reviews the photovoltaic technology, its power generating capability, the different existing light absorbing materials used, its environmental aspect coupled with a variety of its applications. The different existing performance and reliability evaluation models, sizing and control, grid connection and distribution have also been discussed.

Contents

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1. Introduction

Photovoltaic conversion is the direct conversion of sunlight into electricity without any heat engine to interfere. Photovoltaic devices are rugged and simple in design requiring very little maintenance and their biggest advantage being their construction as stand-alone systems to give outputs from microwatts to megawatts. Hence they are used for power source, water pumping, remote buildings, solar home systems, communications, satellites and space vehicles, reverse osmosis plants, and for even megawatt-scale power plants. With such a vast array of applications, the demand for photovoltaics is increasing every year.

Source: Survey of Energy Resources 2007, World Energy Council.

2. Photovoltaic power generation

A photovoltaic power generation system consists of multiple components like cells, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output. These systems are rated in peak kilowatts (kWp) which is an amount of electrical power that a system is expected to deliver when the sun is directly overhead on a clear day.

A grid connected system is connected to a large independent grid which in most cases is the public electricity grid and feeds power into the grid. They vary in size from a few kWp for residential purpose to solar power stations up to tens of GWp. This is a form of decentralized electricity generation. Poponi assessed the prospects for diffusion of photovoltaic (PV) technology for electricity generation in grid-connected systems by the methodology of experience curves that is used to predict the different levels of cumulative world PV shipments required to reach the calculated break-even prices of PV systems, assuming different trends in the relationship between price and the increase in cumulative shipments [1]. Rehman et al. utilized monthly average daily global solar radiation and sunshine duration data to study the distribution of radiation and sunshine duration over Saudi Arabia and also analyzed the renewable energy production and economical evaluation of a 5 MW installed capacity photovoltaic based grid connected power plant for electricity generation [2]. Al-Hasan et al. discussed optimization of the electrical load pattern in Kuwait using grid connected PV systems as the electric load demand can be satisfied from both the photovoltaic array and the utility grid and found during the performance evaluation that the peak load matches the maximum incident solar radiation in Kuwait, which would emphasize the role of using the PV station to minimize the electrical load demand and a significant reduction in peak load can be achieved with grid connected PV systems [3].

Ito et al. studied a 100 MW very large-scale photovoltaic power generation (VLS-PV) system which is to be installed in the Gobi desert and evaluated its potential from economic and environmental viewpoints deduced from energy payback time (EPT), life-cycle CO_2 emission rate and generation cost of the system [4]. Zhou et al. performed the economic analysis of power generation from floating solar chimney power plant (FSCPP) by analyzing cash flows during the whole service period of a 100 MW plant [5]. Muneer et al. explored the long term prospects of large scale PV generation in arid/semi-arid locations, around the globe and its transmission using hydrogen as the energy vector [6]. Cunow et al. described the megawatt plant at the new Munich Trade Fair Centre that represents a significant advance in large PV plant technology, both in terms of system technology and the components employed, operational control and costs [7].

Bhuiyan et al. studied the economics of stand-alone photovoltaic power system to test its feasibility in remote and rural areas of Bangladesh and compared renewable generators with non-renewable generators by determining their life cycle cost using the method of net present value analysis and showed that life cycle cost of PV energy is lower than the cost of energy from diesel or petrol generators in Bangladesh and thus is economically feasible in remote and rural areas of Bangladesh [8]. Alazraki and Haselip assessed the impact of small-scale PV systems installed in homes, schools and public buildings over the last six years under the PERMER (Renewable Energy Project for the Rural Electricity Market) co-funded by a range of public and private sources and the structure of financial subsidies has enabled these remote rural communities to receive an electricity supply replacing traditional energy sources [9]. Kivaisi presented the installation and use of a 3 kWp photovoltaic (PV) plant at Umbuji village, in Zanzibar, Tanzania that was intended to provide power supply for a village school, health centre, school staff quarters, and mosques [10]. Bansal et al. developed an integration of solar photovoltaics of 25 kWp capacity in an existing building of the cafeteria on the campus of the Indian Institute of Technology, Delhi by creating a solar roof covering with the photovoltaic array inclined at an angle of 15° from the horizontal and faces due south [11]. Ubertini and Desideri studied a 15 kWp photovoltaic plant and solar air collectors coupled with a sun breaker structure that was installed on the roof of a scientific high school [12].

3. Hybrid photovolatic power generation

Hybrid power generation system combines a renewable energy source (PV in this case) with other forms of generation, usually a conventional generator powered by diesel or even another renewable form of energy like wind. Such hybrid systems serve to reduce the consumption of non renewable fuel.

Barton et al. described a novel method of modelling an energy store used to match the power output from a wind turbine and a solar PV array to a varying electrical load and validated the method against time-stepping methods showing good agreement over a wide range of store power ratings, store efficiencies, wind turbine capacities and solar PV capacities [13]. Katti and Khedkar investigated the application of wind-alone, solar-alone, and integrated wind PV generation for utilization as stand-alone generating systems, to be used at the remote areas which was based on the site matching and an energy flow strategy that satisfies the need with optimum unit sizing [14]. Deshmukh et al. described methodologies to model hybrid renewable energy system (HRES) components, HRES designs and their evaluation showing that the hybrid PV/wind energy systems are becoming increasingly popular and highlighted the issues related to penetration of these energy systems in the present distribution network as it provides prospects of incorporating in power generation capacity to improve power quality, due to the dispersed generation [15]. Bitterlin attempted to explore the current practicalities of the combination of wind and PV power generation and an energy storage system power generation solution for cellular phone base stations [16]. Prasad et al. presented a procedure for optimizing the size of integrated

wind, photovoltaic system with battery backup, the design of optimal size of the systems being based on the calculated values of life cycle unit cost (LUC) of power generation or relative excess power generated (REPG) or unutilized energy probability (UEP) for a specified deficiency of power supply probability (DPSP) [17].

El-Shatter et al. designed a hybrid photovoltaic(PV)-fuel cell generation system employing an electrolyzer for hydrogen generation and applied a fuzzy regression model (FRM) for maximum power point tracking to extract maximum available solar power from PV arrays under variable insolation conditions [18]. Maclay et al. developed a model of a solar–hydrogen powered residence, in both stand-alone and grid-parallel configuration using Matlab/Simulink that assesses the viability of employing a regenerative fuel cell (RFC) as an energy storage device to be used with photovoltaic (PV) electrical generation and investigated the design requirements of RFC sizing, battery sizing, charge/discharge rates, and state of charge limitations [19]. Zervas et al. studied a hybrid power generation system consisting of the following main components: Photovoltaic Array (PV), Electrolyser, Metal Hydride Tanks, and Proton Exchange Membrane Fuel Cells (PEMFC) that can efficiently store solar energy by transforming it to hydrogen, which is the fuel supplied to the fuel cell [20].

Nelson et al. presented unit sizing and an economical evaluation of a hybrid wind/PV/fuel cell(FC) generation system and a cost comparison with a wind/PV/battery system for a typical home in the US Pacific Northwest and the current cost figures as well as the break-even line distance comparison showed a clear economic advantage of the traditional wind/PV/battery system over the wind/PV/FC/electrolyser system, indicating a need for research and technological advances in the FC/electrolyser area [21]. El-Shatter et al. proposed an energy system comprising three energy sources, namely PV, wind and fuel cells each of which is controlled so as to deliver energy at optimum efficiency employing fuzzy logic control to achieve maximum power tracking for both PV and wind energies and to deliver the maximum power to a fixed dc voltage bus [22].

Shaahid et al. analysed long-term solar radiation data of Dhahran (East-Coast, K.S.A.) to assess the techno-economic feasibility of utilizing hybrid PV–diesel–battery power systems to meet the load of a typical residential building and exhibited that for a given hybrid PV–diesel configuration, the number of operational hours of diesel generators decreases with increase in PV capacity and the decrease in diesel run time is further enhanced by inclusion of battery storage [23]. Helal et al. conducted a techno economic study to analyze the economic feasibility of three alternative designs and the design options include a diesel-assisted PV-RO plant, a fully diesel driven RO plant and a fully solar-driven PV-RO plant and performed detailed cost calculations for each one of the suggested configurations to assess their feasibility and cost effectiveness [24]. Schmid and Hoffmann presented simulations showing that PV systems with energy storage connected to existing diesel generators that can be turned off during the day provide the lowest energy costs [25].

4. Light absorbing materials

All solar cells require a light absorbing material which is present within the cell structure to absorb photons and generate free electrons via the photovoltaic effect. The photovoltaic (PV) effect is the basis of the conversion of light to electricity in photovoltaic, or solar cells. Sunlight, which is pure energy, on striking a PV cell, imparts enough energy to some electrons (negatively charged atomic particles) to raise their energy level and thus free them. A built-in-potential barrier in the cell acts on these electrons to produce a voltage, which in turn is used to drive a current through a circuit.

4.1. Silicon

Bruton asserted that silicon technology has been the dominant one for the supply of power modules into photovoltaic applications and the likely changes are an increasing proportion of multi-crystalline silicon and monocrystalline silicon being used for high-efficiency solar cells while thinner wafers and ribbon silicon technology continue to grow [26]. Braga et al. reviewed the recent advances in chemical and metallurgical routes for photovoltaic (PV) silicon production and found that production of (solar-grade silicon) SoGSi (expand the acronym) can be five times more energy efficient than the conventional Siemens process that uses more than 200 kWh/kg [27]. Goetzberger et al. briefed the history of photovoltaic materials and tried to look at possible future scenarios with silicon as main concern [28]. Van der Zwaan and Rabl presented current PV production cost ranges, both in terms of capacity installation and electricity generation, of single crystalline silicon, multi-crystalline silicon, amorphous silicon and other thin film technologies assessing possible cost reductions as expected according to the learning-curve methodology [29]. Aouida et al. investigated the structural and optical stability of porous silicon layers (PSLs) planned to be used in silicon solar cells technology with UV irradiations applied to PS-treated solar cells improving their PV characteristics [30]. Keogh et al. suggested that testing of silicon solar cells under natural sunlight is simpler, cheaper, and more accurate than all but the most careful simulator measurements [31]. Hanoka discussed a silicon ribbon growth method, String Ribbon comparing it with the two other vertical ribbon technologies discussing the characterization of this ribbon, particularly dislocation distribution and detailed the growth progress of 100 μm ribbon [32].

Schlemm et al. presented a magnetic field enhanced linear microwave plasma source and its application for deposition of silicon nitride anti-reflective and passivation layers on photovoltaic cells [33]. McCann et al. showed that excellent bulk lifetimes and surface passivation can be maintained with a low pressure chemical vapour deposition (LPCVD) silicon nitride layer deposited on a silicon wafer, even following high-temperature treatments, provided a thin layer of silicon oxide is present under the nitride [34].

Adamian et al. investigated the possibility of using porous silicon layers as antireflection coating instead of antireflection coatings in common silicon solar cells (ZnS) and made comparison of the photovoltaic and optical characteristics of investigated samples of solar cells with ZnS antireflection coating and with porous silicon antireflection coating [35]. Balenzategui et al. focused on the measurement of the angular response of solar cells based on different silicon technologies and analysed the sources of deviation from the theoretical response, especially those due to the surface reflectance [36].

4.1.1. Amorphous silicon

Amorphous (uncrystallized) silicon is the most popular thin-film technology with cell efficiencies of 5–7% and double- and triple-junction designs raising it to 8–10%. But it is prone to degradation. Some of the varieties of amorphous silicon are amorphous silicon carbide (a-SiC), amorphous silicon germanium (a-SiGe), microcrystalline silicon (μc-Si), and amorphous silicon-nitride (a-SiN).

Yang et al. discussed the advances made in amorphous-Si PV technology that led to the achievement of an AM 1.5, 13% stable cell efficiency and set the foundation for the spectrum splitting triple-junction structure being manufactured by the roll-to-roll continuous deposition process [37]. Lund et al. reported on lab-

oratory and field studies being undertaken on the nature of the Staebler–Wronski effect in amorphous silicon solar cells and how the stability of these cells is affected by different operating conditions and proposed a number of possible ways to reduce the Staebler–Wronski effect in a-Si:H solar cells [38]. Tawada et al. developed a series of production technologies for stable 8% efficiency direct-super-straight-type modules along with large area a-Si deposition technique [39].

4.1.2. Crystalline silicon

Crystalline silicon offers an improved efficiency when compared to amorphous silicon while still using only a small amount of material. The commercially available multi-crystalline silicon solar cells have an efficiency around 14–19%.

Green et al. developed crystalline silicon on glass (CSG) solar cell technology aiming to combine the advantages of standard silicon wafer-based technology with that of thin-films, with the lowest likely manufacturing cost of these contenders and confirmed efficiency for small pilot line modules already in the 8–9% energy conversion efficiency range, on the path to 12–13% [40]. Aberle reviewed the present status of high-throughput plasma-enhanced chemical vapour deposition (PECVD) machines for the deposition of SiN onto c-Si wafers, and the fundamental properties of Si-SiN interfaces fabricated by PECVD [41]. Shah et al. proposed that intrinsic microcrystalline silicon deposited at temperatures as low as 200–250 °C by the VHF–GD (very high frequency-glow discharge) method has been used successfully as photovoltaically active material within p–i–n and n–i–p type solar cells [42]. Lipinski et al. investigated double porous silicon (d-PS) layers formed by acid chemical etching on a top surface of n^+/p multi-crystalline silicon solar cells with the aim to improve the performance of standard screen-printed silicon solar cells, the PS layer serving as an antireflection coating with the efficiency of the solar cells with this structure is about 12% [43]. Dobrzanski et al. proposed a technique of laser texturization for solar cells made of multi-crystalline silicon so as to improve the interaction between laser light and workpiece [44]. Vitanov et al. investigated the influence of the emitter thickness on the photovoltaic properties of monocrystalline silicon solar cells with porous silicon [45]. Wronski et al. studied the nature of protocrystalline Si:H materials, optimization of cell structures and their light-induced degradation [46]. Macdonald et al. described an alternative approach to implementation of the impurity-photovoltaic (IPV) effect in crystalline silicon, referred to as electronically coupled up-conversion that avoids two of the major problems associated with the conventional IPV approach—namely, recombination of minority carriers generated in the base by a single photon, and parasitic absorption [47].

Franklin et al. described the novel sliver cells made of single crystal silicon solar cells that offer the potential for a 10–20 times reduction in silicon consumption for the same sized solar module, while also having the added benefit, in an industrial production environment, of requiring 20–40 times fewer wafer starts per MW than for conventional wafer-based technologies [48].

4.2. Cadmium telluride (CdTe) and cadmium sulphide (CdS)

Ferekides et al. presented work carried out on CdTe/CdS solar cells fabricated using the close spaced sublimation (CSS) process that has attractive features for large area applications such as high deposition rates and efficient material utilization [49]. Pfisterer demonstrated the influence of surface treatments of the cells (Cu_2S–CdS) and of additional semiconducting or metallic layers of monolayer-range thicknesses at the surface and discussed effects of lattice mismatch on epitaxy as well as wet and dry-topotaxy and preconditions for successful application of topotaxy [50]. Richards et al. demonstrated using ray-tracing simulations that the short-wavelength response of cadmium sulfide/cadmium telluride (CdS/CdTe) photovoltaic (PV) modules can be improved by the application of a luminescent downshifting (LDS) layer to the PV module that exhibit a poor internal quantum efficiency [51].

4.3. Organic and polymer cells

Jørgensen et al. presented an understanding of stability/degradation in organic and polymer solar cell devices and discussed the methods for studying and elucidating degradation and enhancing the stability through the choice of better active materials, encapsulation, application of getter materials and UV-filters [52]. Bernede et al. studied different cell configurations: two-layers D/A organic solar cells deposited by vacuum evaporation and bulk D/A heterojunction material based on a discontinuous D/A network thin film obtained by spin coating [53]. Wei et al. demonstrated efficient white organic light-emitting device based on exciplex with higher luminance and luminous efficiency and this bi-functional device with electroluminescence (EL) and PV performances is promising to be used as white displays or backlight source in the future as it can be charged by solar energy through additional apparatus free of work and can also be used as an optical sensor to UV light [54]. Yue et al. developed an organic PV device based on triplet complex Re-Phen with power conversion efficiency of 4% which is high compared to the devices based other metal complexes, state increasing the PV efficiency owing to the existence of a charge transfer(CT) absorption [55]. Mozer et al. presented successful strategies towards improved photovoltaic performance using various novel materials, including double-cable polymers, regioregular polymers and low bandgap polymers demonstrating that the bulk heterojunction concept is a viable approach towards developing photovoltaic systems by inexpensive solution-based fabrication technologies [56].

4.4. Hybrid photovoltaic cell

Itoh et al. conducted electrical output performances of 'democratic module photovoltaic system' consisting of amorphous-, polycrystalline- and crystalline-silicon-based solar cells that reveal significant differences, mainly with respect to seasonal variation and found that the annual output energy generated by amorphous-Si-based solar cell is about 5% higher than that of crystalline-Si-based arrays [57]. Wu et al. proposed a new technique of maximum power point controller, through which the proposed hybrid PV system could adopt amorphous Si solar cell together with crystalline Si solar cell to realize a PV system with higher ratio of performance to cost [58]. Olson et al. fabricated hybrid poly(3-hexylthiophene)P3HT/nanostructured zinc oxide devices using solution-based methods with efficiencies greater than 0.5% [59].

4.5. Thin film technology

Thin-film solar cells are basically thin layers of semiconductor materials applied to a solid backing material. Thin films greatly reduce the amount of semiconductor material required for each cell when compared to silicon wafers and hence lowers the cost of production of photovoltaic cells. Gallium arsenide (GaAs), copper, cadmium telluride (CdTe) indium diselenide ($CuInSe_2$) and titanium dioxide (TiO_2) are materials that have been mostly used for thin film PV cells.

Barnett et al. investigated that solar cells utilizing thin-film polycrystalline silicon can achieve photovoltaic power conversion efficiencies greater than 19% as a result of light trapping and back surface passivation with optimum silicon thickness [60]. Aberle reviewed the most promising thin-film c-Si PV technologies that

have emerged during the last 10 years and found that three different thin-film c-Si PV technologies (SLIVER, hybrid, CSG) can be transferred to industrial production [61]. Fave et al. compared epitaxial growth of silicon thin film on double porous sacrificial layers obtained by liquid or vapor phase epitaxy (LPE or VPE) and found that mobility and diffusion length are sligtly higher with VPE compared to LPE fabricating solar cells using a detached film obtained with VPE and without any surface passivation treatment or antireflective coating, exhibits an efficiency of 4.2% with a fill factor of 0.69 [62]. Sagan et al. studied reflection high-energy electron diffraction (RHEED) pattern of CdTe and HgCdTe thin films grown on Si by pulse laser deposition [63]. Solanki et al. described a process of transferring thin porous silicon layers (PSL) onto a ceramic substrate like alumina [64].

Powalla et al. assessed that all existing thin-film PV technologies, especially the $Cu(In,Ga)Se_2$ (CIGS)-based technology, have a high cost reduction potential at high production volumes projecting futuristic challenge to combine high production volumes with high throughput, sufficient yield and superior quality to achieve efficiencies of above 11% and a maximum of 12.7% [65]. Hollingsworth et al. demonstrated based on thin-film fabrication studies that ternary single source precursors can be used in either a hot, or cold-wall spray chemical vapour deposition reactor, for depositing $CuInS_2$, $CuGaS_2$ and $CuGaInS_2$ at reduced temperatures (400–450 °C), which display good electrical and optical properties suitable for photovoltaic devices [66].

Ito et al. presented techniques of TiO_2 film fabrication for dye-sensitized solar cells that consists of pre-treatment of the working photoelectrode by $TiCl_4$, variations in layer thickness of the transparent nanocrystalline-TiO_2 and application of a topcoat light-scattering layer as well as the adhesion of an anti-reflecting film to the electrode's surface resulting in a conversion efficiency of global air mass 1.5 (AM 1.5, 1000 W/m^2) solar light to electric power over 10% [67].

Messina et al. presented a methodology to deposit Sb_2S_3 thin films of 500–600 nm in thickness that are adequate for use in photovoltaic structures from a single bath along with the differences in the film thickness and improvement in the crystallinity and photoconductivity upon annealing the film in nitrogen [68]. Liehr et al. proposed Microwave Plasma Enhanced Chemical Vapour Deposition (PECVD) of thin films when highest deposition rates and/or high fragmentation of precursor material is desirable for photovoltaic applications [69]. Sathyamoorthy et al. discussed the electrical transport properties of flash evaporated Zinc Phthalocyanine thin films and studied the DC conduction mechanism in these films (Al–ZnPc–Al structure) at different temperatures along with the field dependence behaviour on activation energy and possible conduction mechanism in the ZnPc films under DC field [70].

4.6. Some other solar cells

Mainz et al. demonstrated that rapid thermal sulphurisation of sputtered Cu/In precursor layers is suitable for industrial production of thin film photovoltaic modules [71]. Yoosuf et al. investigated the effect of sulfurization temperature and time on the growth, structural, electrical and photoelectrical properties of b-In_2S_3 films [72]. Nishioka et al. evaluated the temperature dependences of the electrical characteristics of InGaP/InGaAs/Ge triple junction solar cells under concentration and found that for these solar cells, conversion efficiency decreased with increasing temperature, and increased with increasing concentration ratio owing to an increase in open-circuit voltage (V_{oc}) [73]. Antolín et al. investigated the photocurrent produced by double-absorption of sub band gap photons predicted by the IBSC model that has been measured in QD-IBSCs (Quantum dot-Intermediate band solar cells) fabricated with InAs/GaAs material using a modulated technique with two light beams [74]. Woods et al. discussed the performance, testing, and problems of copper indium aluminum diselenide (CIAS) thin-film devices with CIAS co-evaporated in a large-area moving substrate deposition system on transparent back contact technology [75]. Phani et al. described the titania solar cells that converts sunlight directly into electricity through a process similar to photosynthesis and has performance advantages over other solar cells, which include the ability to perform well in low light and shade, and to perform consistently well over a wide range of temperatures and low cost [76]. Grätzel proposed the dye-sensitized nanocrystalline electrochemical photovoltaic system that has become a validated and credible competitor to solid-state junction devices for the conversion of solar energy into electricity and its the prototype of a series of optoelectronic and energy technology devices exploiting the specific characteristics of this innovative structure for oxide and ceramic semiconductor films with an incident photon (standard AM 1.5) to current conversion efficiencies (IPCE) over 10% [77].

5. Performance and reliability

Researchers and scientists had developed and proposed various methods for evaluation of performance of a photovoltaic system. A brief review of these methods is presented here.

Li et al. investigated the operational performance and efficiency characteristic of a small PV system installed at the City University of Hong Kong and the amount of solar irradiance data falling on the PV panel was determined using the luminous efficacy approach [78]. Yu et al. developed a novel two-mode maximum power point tracking (MPPT) control algorithm combining the modified constant voltage control and incremental conductance method (IncCond) method to improve the efficiency of the 3 kW PV power generation system at different insolation conditions that provides excellent performance at less than 30% insolation intensity, covering the whole insolation area without additional hardware circuitry [79]. Huang et al. proposed a PV system design, called "near-maximum power-point-operation" (nMPPO) that can maintain the performance very close to PV system with MPPT (maximum-power-point tracking) but eliminate the hardware of the MPPT and the long term performance simulation shows that the overall nMPPO efficiency is higher than 93% [80]. Jaber et al. developed a computer-simulation model of the behaviour of a photovoltaic (PV) gas-turbine hybrid system, with a compressed-air store, to evaluate its performance as well as to predict the total energy-conversion efficiency and found that hybrid plant produces approximately 140% more power per unit of fuel consumed compared with corresponding conventional gas turbine plants and lower rates of pollutant emissions to the atmosphere per kWh of electricity generated [81]. Stoppato presented the results of a life cycle assessment (LCA) of the electric generation by means of photovoltaic panels [82]. Wiemken et al. studied effects of combined power generation by monitoring data from 100 PV systems that reveals a considerable decrease in power fluctuations compared to an individual system and the energy spectrum of combined power generation showed that produced energy is generated in a range below 65% of the overall installed power [83]. Keogh et al. presented a new tester (commonly used for measuring solar cells and modules) design that is simple, low cost, and reduces transient errors by use of a constant voltage cell-bias circuit and it extracts a family of *I–V* curves over a decade range of light intensity, which provides comprehensive information on cell performance [84]. So et al. analyzed and evaluated the performance of a large scale grid-connected PV system and monitoring system that are installed at SSDP in Daegu City in order to observe the overall effect of meteorological conditions on their operation characteristics for monitoring period [85].

Mahmoud et al. investigated the potential of PV applications in Palestine, identifying the barriers for prevalence of PV applications as in other countries and demonstrated the reliability and feasibility of utilizing PV systems by presenting the test results of a PV system by supplying a rural clinic with its power demands [86]. El-Tamaly and Mohammed presented a fuzzy logic technique to calculate and assess the reliability index for each Photovoltaic (PV)/Wind Energy System (WES) Hybrid Electric Power System (PV/WES HEPS) HEPS configuration under study and determined the impact of interconnecting PV/WES HEPS into Utility Grid (UG) [87]. Tanrioven presented a simulation methodology for reliability and cost assessment of the energy sources such as wind, solar energy and fuel cell (FC) in an independent micro-grid (IMG) system, which is a distribution system with distributed energy sources such as microturbine, photovoltaic and fuel cells and developed a systematic technique and a computer program for reliability and cost assessment of the IMG system containing Fuel Cell (FC), photovoltaic (PV) and wind energy (WE) [88]. Stember presented a systems level approach for reliability analyses for solar photovoltaic systems and illustrated the usefulness of these analyses in photovoltaic systems design [89].

6. Environmental aspects

Tezuka et al. proposed a new method for estimating the amount of CO_2-emission reduction in the case where the carbon-tax revenue is used as the subsidy to promote PV-system installations and concluded that the amount of CO_2-emission reduction increases by advertising the PV system with subsidy policy even under the same tax-rate and the CO_2-payback time of the PV system reduces by half if the GDP is assumed not to change after the introduction of carbon taxation [90]. Krauter et al. examined a CO_2 comprehensive balance within the life-cycle of a photovoltaic energy system and found that the actual effect of the PV system in terms of net reduction of carbon dioxide is the difference between the sum of electrical yield related to the local grid and the value for recycling and the sum of the production requirements and the transport emissions [91]. Fthenakis and Kima studied solar- and nuclear-electricity-generation technologies' entire lifecycle of energy production; carbon dioxide and other gases emitted during the extraction, processing, and disposal of associated materials and determined the greenhouse gas (GHG) emissions, namely, CO_2, CH_4, N_2O, and chlorofluorocarbons due to materials and energy flows throughout all stages of the life of commercial technologies for solar–electric and nuclear-power generation [92]. Kannan et al. performed life cycle assessment (LCA) and life cycle cost analysis for a distributed 2.7 kWp grid-connected monocrystalline solar PV system operating in Singapore and provided various energy payback time (EPBT) analyses of the solar PV system with reference to a fuel oil-fired steam turbine and their greenhouse gas (GHG) emissions and costs are also compared revealing that GHG emission from electricity generation from the solar PV system is less than one-fourth that from an oil-fired steam turbine plant and one-half that from a gas-fired combined cycle plant [93]. Tsoutsos et al. presented an overview of an Environmental Impact Assessment for central solar systems, to estimate the magnitude of potential environmental impacts and proposed appropriate mitigation measures, can play a significant role to proper project design and to a subsequent project public acceptance [94]. Pacca et al. assessed the modeling parameters that affect the environmental performance of two state-of-the-art photovoltaic (PV) electricity generation technologies: the PVL136 thin film laminates and the KC120 multi-crystalline modules [95]. Hondo presented the results of a life cycle analysis (LCA) of greenhouse gas emissions from power generation systems in order to understand the characteristics of nine different types of power generation systems that included solar-photovoltaic (PV) from the perspective of global warming and life cycle greenhouse gas (GHG) emission per kWh of electricity generated was estimated for the systems using a combined method of process analysis and input–output analysis [96].

7. Sizing, distribution and control

Hernandez et al. presented a systematic algorithm to determine the optimal allocation and sizing of Photovoltaic Grid-connected Systems (PVGCSs) in feeders that reaches the best compromise for both technical and economical aspect by multi-objective optimization approach and is robust with moderate computer requirements [97]. Kaushika et al. investigated a stand-alone solar PV systems with interconnected arrays for optimal sizing of the array and battery bank using the system simulation modeling, which considers the electricity generation in the array and its storage in the battery bank serving the fluctuating load demand and used the loss of power supply probability (LPSP) to connote the risk of not satisfying the load demand [98]. Yang et al. developed the Hybrid Solar-Wind System Optimization Sizing (HSWSO) model, to optimize the capacity sizes of different components of hybrid solar–wind power generation systems employing a battery bank [99]. Koutroulis et al. proposed a methodology for optimal sizing of stand-alone photovoltaic wind generation (PV/WG) systems that suggests, among a list of commercially available system devices, the optimal number and type of units ensuring that the 20-year round total system cost is minimized subject to the constraint that the load energy requirements are completely covered, resulting in zero load rejection implementing the cost (objective) function minimization using genetic algorithms [100]. Burger et al. discussed the influence of time resolution of solar radiation data on the correct sizing of PV plants [101].

Conti et al. studied the voltage profile of a LV feeder in order to assess the maximum value of the power that can be injected into multiple load points of the feeder by PV units without violating the voltage constraints and showed that with reference to a set of contiguous generation units, it is possible to derive analytical relationships between the position of the point of maximum/minimum voltage on the feeder and the characteristics of the distributed generation [102]. Paatero et al. analysed the effects of a high level of grid connected PV in the middle voltage distribution network and emphasised on static phenomena, including voltage drop, network losses and grid benefits using a multi-purpose modeling tool and demonstrated that high penetration levels of PV power generation may cause voltage problems in the electrical network [103]. Conti and Raiti dealt with the solution of the Load flow (LF) problem in distribution networks with photovoltaic (PV) distributed generation (DG) and used suitable models incorporated in a radial distribution probabilistic load flow (PLF) program that has been developed by using Monte Carlo techniques for prediction of the active power produced by PV DG units and the power absorbed by the loads are used to represent the uncertainty of solar energy availability and load variations and the developed program allows probabilistic predictions of power flows at the various sections of distribution feeders and voltage profiles at all nodes of a network [104].

Contreras et al. presented the control system for an installation for producing hydrogen via electrolysis using a 250 kWp photovoltaic generator and the electrical transmission ratio of the whole hydrogen generation plant, calculated by the coefficient between the electrical power delivered to the hydrolyser and the power output from the photovoltaic generator, is around 94% because of the reduction in loss due to the design of the transformer, as well as the controller switching the power elements using intel-

ligent power modules (IPM) and pulse width modulation (PWM) [105].

8. Storage systems

A widely used method of storing electricity is electrochemical-battery storage. Hua et al. discussed the behaviour of GFMU valve-regulated lead-acid (VRLA) batteries during three cycling test procedures, and that of batteries in practical stand-alone PV systems and the cycling test results showed that GFMU VRLA batteries display good cycle life and could be successfully used for stand-alone photovoltaic application in northwest areas of China [106]. Lambert et al. proposed VRLA batteries based on gel electrolyte, bismuth-bearing lead oxide and tetra basic lead sulfate in the cured plate product technologies that represent the most suitable solution to the challenge of providing a state-of-the-art battery for the solar lantern project [107].

9. Concentrator

Concentrating photovoltaic systems make use of a large area of lenses or mirrors in order to focus sunlight on a small area of photovoltaic cells. The systems using single or dual-axis tracking to enhance performance, can be referred to as Heliostat Concentrator Photovoltaics (HCPV) their primary attraction being the reduced usage of semiconducting material which is expensive and increasing the concentration ratio. The limitations being the costs of focusing, tracking and cooling equipment.

Mallick et al. designed, constructed and experimentally characterised a novel non-imaging asymmetric compound parabolic photovoltaic concentrator (ACPPVC) with different numbers of PV strings connected in series experimentally characterised under outdoor conditions both with and without concentrators showing that the use of an ACPPVC increased the maximum power point by 62% (i.e. the power by a factor of 1.62) when compared to a similar non-concentrating PV panel [108]. Matsushima et al. described a non-sun-tracking concentrating solar module that is designed to achieve photovoltaic (PV) systems with higher generation power density that consists of a solar panel having a higher tilt angle than that of a conventional one and with a solar reflector placed in front of the solar panel on a downward inclination angle towards the panel resulting in increased electricity delivered by 1.5 compared to conventional module and also reduced total area of solar panels in PV systems [109]. Rosell et al. presented a prototype 11× concentration rate and two axis tracking system with a novelty of coupling of a linear Fresnel concentrator with a channel photovoltaic/thermal collector and the measured thermal performance of the solar system gave values above 60% with theoretical analysis confirming the thermal conduction between the PV cells and the absorber plate to be a critical parameter [110]. Feuramann et al. proposed the solar miniature paraboloidal dish that can produce flux levels that are deemed to be high for solar cells in a practical, high-efficiency fashion for concentrating photovoltaic systems [111]. Quaschning performed detailed technical and economical analyses computer simulations pointing out differences of solar thermal parabolic trough power plants, non-tracked and two-axis-tracked PV systems [112]. Huang et al. proposed a new design idea of a one axis three position tracking PV module with low concentration ratio reflector where every PV module is mounted on an individual sun tracking frame and the one axis tracking mechanism adjusts the PV position only at three fixed angles (three position tracking): morning, noon and afternoon and performed a design analysis of the one axis three position sun tracking PV module [113]. Schuler et al. proposed that quantum dot containing nanocomposite coatings might be an alternative for the production of planar quantum dot solar concentrators [114]. Gallagher et al. described a non-tracking concentrator, which uses nano-scale quantum dot technology to render the concept of a fluorescent dye solar concentrator (FSC) which is a practical proposition [115].

10. Application

The increasing efficiency, lowering cost and minimal pollution are the boons of the photovoltaic systems that have led to a wide range of their application.

10.1. Building integrated systems

Building-integrated photovoltaic (BIPV) systems incorporate photovoltaic properties into building materials such as roofing, siding, and glass and thus offer advantages in cost and appearance as they are substituted for conventional materials in new construction. Moreover the BIPV installations are architecturally more appealing than roof-mounted PV structures. Yoo et al. proposed a building design to have the PV modules shade the building in summer, so as to reduce cooling loads, while at the same time allowing solar energy to enter the building during the heating season to provide daylight and conducted an analysis of the system performance, evaluation of the system efficiency and the power output [116]. Bakos et al. described the installation, technical characteristics, operation and economic evaluation of a grid-connected building integrated photovoltaic system (BIPV) and the technical and economical factors were examined using a computerized renewable energy technologies (RETs) assessment tool [117]. Ordenes et al. analysed the potential of seven BIPV technologies implemented in a residential prototype simulated in three different cities in Brazil and performed simulations using the software tool EnergyPlus to integrate PV power supply with building energy demand [118]. Xu et al. developed and evaluated the performance of an Active Building Envelope (ABE) systems, a new enclosure technology with the ability to regulate their temperature (cooling or heating) by interacting with the sun which integrates photovoltaic (PV) and thermoelectric (TE) technologies [119] Chow et al. described effectiveness of cooling by means of a natural ventilating air stream numerically based on two cooling options with an air gap between the PV panels and the external facade: (i) an open air gap with mixed convective heat transfer, and (ii) a solar chimney with buoyancy-induced vertical flow and found that effective cooling of a PV panel can increase the electricity output of the solar cells [120]. Wong et al. proposed semi-transparent PV top light material for residential application with 50% radiation transmission rate contributing to a maximum of 5.3% reduction in heating and cooling energy consumption when compared with a standard BIPV roof [121]. Cheng et al. developed an empirical approach for evaluating the annual solar tilted planes irradiation with inclinations from 0 to 90° and azimuths from 0 to 90° on building envelopes for BIPV applications in Taiwan [122]. Ricardo Ruther et al. studied the behavior of grid connected, building integrated photovoltaic(BIPV) solar energy conversion in the urban environment of a metropolitan area in a Brazilian state capital, aiming at maximizing the benefits of the distributed nature of PV generation [123]. Jardim et al. studied the behaviour of grid-connected, building integrated photovoltaic solar energy conversion in the built environment of a metropolitan area in Brazilian state capital, aiming at maximising the benefits of the distributed nature of PV generation [124].

10.2. Desalination plant

Lamei et al. discussed electricity price at which solar energy can be considered economical to be used for RO (Reverse Osmosis) desalination that is independent of RO plant capacity and proposed

an equation to estimate the unit production costs of RO desalination plants that can be used to calculate unit production costs for desalinated water using photovoltaic (PV) solar energy based on current and future PV module prices [125]. Kershrnan et al. studied an experimental plant for seawater reverse osmosis(SWRO) desalination powered from renewable energy sources (RES) at Libya's coast of the Mediterranean sea with both wind energy conversion (WEC) and photovoltaic power generation (PV) being integrated into a grid connected power supply for a reverse osmosis (RO) desalination plant with power recovery [126]. Hasnain et al. proposed a simple single-effect solar still plant with a capacity of 5.8 m^3 per day for the treatment of reject brine obtained from Sadous PV-powered RO desalination plant that can be configured as a 100% solar powered desalination system for any location and quality of brackish water and found that the single effect solar stills for small scale plants is more viable to use in remote area, where the land value is negligible as solar stills are easy to install and maintained and can be fabricated with locally available materials [127]. El-Sayed modeled desalination by spiral-wound RO membrane modules driven by solar to power photovoltaic converter panels with the purpose of revealing the economic potential of the combination [128]. Weiner et al. presented the designing, erection and operation process of a stand-alone desalination plant powered by both solar photovoltaic and wind energy [129].

10.3. Space

Habraken et al. presented a trade-off study in the field of space solar arrays and concentration. that defines the parameters to evaluate whether a given concept (cell type, concentrator) becomes appropriate as two different trough concentrators, and a linear Fresnel lens concentrator are compared to rigid arrays and thermal and optical behaviors are analysed [130]. Seboldt et al. a developed a new design for an Earth-orbiting Solar Power Satellite (SPS) called "European Sail Tower SPS" featuring an extremely lightweight and large tower-like orbital system with the capability to supply Europe with significant amounts of electrical power generated by photovoltaic cells and subsequently transmitted to Earth via microwaves [131]. Girish studied the possibility of nighttime photovoltaic power generation in planetary bodies like moon using reflected light energy flux from nearby planetary objects based on latest low-intensity low-illumination (LILT) solar cell technology [132].

10.4. Solar home systems

Bond et al. described current experience and trials in East Timor with solar photovoltaic (PV) technology by introduction of solar home systems (SHS) [133]. Posorski et al. proposed Solar Home Systems (SHS) that are commercially disseminated and used them cost efficiently to substitute kerosene and dry cell batteries to reduce GHG emissions and thus make a significant contribution to climate protection [134].

10.5. Pumps

Pande et al. designed and developed a Solar Photovoltaic operated (PV) pump drip irrigation system for growing orchards in arid region considering different design parameters like pump size, water requirements, the diurnal variation in the pressure of the pump due to change in irradiance and pressure compensation in the drippers [135]. Meah et al. discussed some policies to make solar photovoltaic water pumping (SPVWP) system an appropriate technology for the respective application region as it has proved its aspects technically, economically, and environmentally in developed countries [136]. Short et al. investigated some of the issues involved in solar water pumping projects, described the positive and negative effects that they can have on the community and proposed an entirely new type of pump, considering the steps that could be taken to ensure future sustainability [137]. Chandratilleke et al. tested the performance of water pumping system comprising a photovoltaic array of 1.14 kW power and a centrifugal pump of 860 W power and found its suitability for medium (1–4 m^3/h) delivery flow-rate applications, although the overall operating efficiency is low at around 1.6% [138]. Badescu analyzed the operation of a complex time dependent solar water pumping system consisting of four basic units: a PV array, a battery, a DC motor, and a centrifugal pump [139].

10.6. Photovoltaic and thermal (PVT) collector technology

Chow et al. described an experimental study of a centralized photovoltaic and hot water collector wall system that can serve as a water pre-heating system using collectors mounted at vertical facades preferring natural water circulation over forced circulation and the thermal efficiency was found 38.9% at zero reduced temperature, and the corresponding electricity conversion efficiency was 8.56% [140]. He et al. proposed the hybrid photovoltaic and thermal (PVT) collector technology using water as the coolant as a solution for improving the energy performance [141]. Vokas et al. studied a photovoltaic–thermal system for domestic heating and cooling concluding that the system can cover a remarkable percentage of the domestic heating and cooling demands [142]. Chow et al. presented a photovoltaic-thermosyphon collector for residential applications with rectangular flow channels and discussed the energy performance [143]. Othman et al. studied a hybrid photovoltaic–thermal (PV/T) solar collector which generates both electricity and heat energy simultaneously and achieved improvements to the total efficiency of the system by the use of a double-pass collector system and fins [144].

10.7. Other applications

Mpagalile et al. fabricated a novel, batch operated oil press, powered by solar PV system designed to suit small-scale oil processors in developing countries with the press providing an opportunity for the processor to use different oilseeds and volumes of the materials being processed by either changing the size of the chamber or adjusting the screw rod to reduce the volume of the upper chamber and for pressing the materials at low or high pressure depending on the expression efficiency required [145]. Knaupp et al. analysed the solar–hydrogen systems regarding their usability as energy supply system for high altitude platforms [146]. Xi et al. presented the development and applications of two solar-driven thermoelectric technologies (i.e., solar-driven refrigeration and solar-driven thermoelectric power generation) and the currently existing drawbacks of the solar-based thermoelectric technology as well as methods to improve and evaluate the performance of the solar-driven thermoelectric devices [147]. Takigawa et al. developed a new concept of "smart power conditioner" with small storage battery for value-added PV application that has a smoothing function to reduce PV output variation and customer's load fluctuation, and also has the additional function to compensate for the harmonics current and reactive power caused by customer's load [148]. Bechinger et al. developed self-powered electrochromic windows where a semi-transparent photovoltaic (PV) cell provides the power to activate an electrochromic system deposited on top of the solar cell and showed that dye-sensitized solar cells and EC (electrochromic) cells can be easily combined [149]. Chow et al. developed an energy model of a PV ventilated window system and conducted the overall performance analysis for different window orientations [150]. Ji et al. presented a novel

photovoltaic/thermal solar-assisted heat pump (PV/TSAHP) system, which can generate electricity and heat energy simultaneously and introduced a mathematical model based on the distributed parameter technique for predicting the dynamic system behavior [151]. Ahmad et al. presented a small PV power system for hydrogen production using the photovoltaic module connected to the hydrogen electrolyzer with and without maximum power point tracker [152].

11. Problems associated with photovoltaics technology

Thongpron et al. investigated the nature of components of complex power (actual, reactive and apparent power) of a PV-grid interactive system due to low radiation, under 400 W/m^2 and found that actual power is available at high values of radiation from a PV array and at low radiation level when the array does not provide enough output power, reactive power is drawn from distribution transformer and fed into an inverter and loads and hence methods must be devised to capture this low radiation energy and converted into actual power form [153]. Denholm et al. examined some of the limits to large-scale deployment of solar photovoltaics (PV) in traditional electric power systems evaluating the ability of PV to provide a large fraction (up to 50%) of a utility system's energy by comparing hourly output of a simulated large PV system to the amount of electricity actually usable and found that under high penetration levels and existing grid-operation procedures and rules, the system will have excess PV generation during certain periods of the year [154]. Lund et al. analysed the problems of integration of electricity production from fluctuating renewable energy sources into the electricity supply illustrating the magnitude of the problem in terms of excess electricity production when different Renewable Energy Sources (RES) are integrated into a Danish reference system with a high degree of Combined Heat and Power (CHP) that takes benefit of the different patterns in the fluctuations of different renewable sources and the purpose has been to identify optimal mixtures from a technical point of view [155]. Stuckings et al. studied shading and resistive loss from the fingers of encapsulated solar cells by measuring the reflection from the front surface of encapsulated silver electroplated front contact solar cells using a spectrophotometer with integrating sphere attachment and found that the effective shading loss is about one third of the coverage fraction of the cell grid because of trapping of light reflected from the grid [156].

12. Future

With the fossil fuels in the verge of exhaustion, the renewable sources are being seen as the prospective potentials for energy. The solar photovoltaic technology is one such source that can looked up to as vast research is being carried out and a significant improvement in performance has been achieved.

Waldau observed that photovoltaics is one of the fastest growing industries worldwide and in order to maintain this growth rate need for new developments with respect to material use and consumption, device design, reliability and production technologies as well as new concepts to increase the overall efficiency arises [157]. Feltrin et al. analyzed several photovoltaic technologies, ranging from silicon to thin films, multi-junction and solar concentrator systems for terawatt level deployment of the existing solar cells, and for each technology, identified improvements and innovations needed for further scale-up [158]. Muneer et al. described solar PV electricity as the solution of future energy challenges and the modular approach adopted to meet the year 2025 energy demand of six major cities in India: Chennai, Delhi, Jodhpur, Kolkata, Mumbai and Trivandrum, indicates that the suggested solar hydrogen based energy network has the capability of providing the energy requirements [159].

13. Conclusion

A review of major solar photovoltaic technologies comprising of PV power generation, Hybrid PV generation, various light absorbing materials, performance and reliability of PV system, sizing, distribution and control is presented. The different applications of solar PV system such as building integrated system, desalination plant, space, solar home systems and pumps are also presented. This paper would be useful for the solar PV system manufactures, academicians, researchers, generating members and decision makers.

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